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METHOD AND APPARUTUS FOR MULTI-BAND OPTICAL SWITCHING USING MULTI-PUMP PARAMETRIC DEVICES
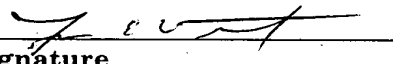
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METHOD AND APPARUTUS FOR MULTI-BAND OPTICAL SWITCHING USING MULTI-PUMP PARAMETRIC DEVICES

FIELD OF THE INVENTION

5   This invention relates to the field of optical switching and, more particularly, to multi-band optical switching using multi-pump parametric devices.

BACKGROUND OF THE INVENTION

10   To date, most communication networks use optical fiber as a point-to-point provider with electro-optical transmitters and receivers providing the conversion of optical signals to electrical signals at important points, e.g. switches, in the network. However, because the net throughput is limited by the electronics, such architectures do not effectively utilize the available bandwidth

15   of the optical fibers used for transmission.

Wavelength-division multiplexing (WDM), as applied to optical communications, impresses several data signals upon respective optical carriers of different wavelengths. The optical signals are combined upon a single optical fiber at its transmitting end. At the receiving end of the optical

20   fiber, the optical carriers are optically demultiplexed into beams each carrying a single data signal, and conventional optical detectors are dedicated to each of these beams. Although this simple WDM architecture increases the fiber throughput by the factor of the number of optical carriers, the nodes of the network become complex and expensive because of the need to convert optical

25   signals to electrical signals at various points in the network. As such, there exists a need for low-cost, highly efficient all-optical switches.

Various prior art concepts have been developed for all-optical WDM networks in which the nodes of the networks switch different ones of the WDM wavelength channels in different directions without ever converting the optical

30   signals to electronic form. For example, early implementations of transparent all-optical networks include wavelength-division multiplexing (WDM) switches which can selectively switch the wavelength-multiplexed optical signals in different directions dependent upon their wavelengths. The signals are not

converted to electrical form at the switches but remain in optical form throughout. In such transparent all-optical networks, access nodes are interconnected through the WDM switches, the destination access node of a signal leaving an originating access node being determined by the wavelength

5   of its optical carrier. The WDM switches are reconfigurable within times of the order of seconds and remain in a set configuration for minutes or even days. The reconfigurability allows the optical wavelengths to be reallocated to connecting different pairs of the access nodes. Such a switching of WDM signals is referred to as space switching even though the signals are switched

10   in different directions with the directions being determined by the wavelength.

It should be noted however, that the number of discrete wavelength channels is limited. For example, a network of sufficient size requires amplification, which at the present time depends upon erbium-doped fiber amplifiers having an amplification bandwidth of about 40 nm. With a realistic

15   optical channel spacing of about 4 nm in a moderately simple architecture, such a bandwidth can accommodate only about 10 optical channels. Hence, wavelength reuse will be required, but the wavelength reuse in such networks is limited. Such limited reuse is insufficient for a network intended to connect large numbers of users in a public network. More extensive wavelength reuse

20   is required. Of perhaps greater importance, on a larger scale, one or more of the access nodes, may simultaneously be connected to another transparent all-optical network with additional access nodes attached to the second network. This architecture allows the overall network to be scaled to very large sizes, however, the scalability requires that an access node connecting the two

25   networks be able to translate the wavelength for the optical carrier of the data signal being transferred between the two all-optical networks to a wavelength dictated by the second network. That is, large WDM networks will require wavelength translation of a signal at many points in the network.

Several switches have been proposed for wavelength translation of a

30   signal in a WDM system. For example, an all-optical switch previously proposed for wavelength translation of a signal is a four-wave optical mixer. Four-wave mixing, however, suffers several disadvantages over difference frequency generation. For a single pump signal, the pump frequency ω_p is

between the two optical carrier frequencies ω_1, ω_2 and the tails of the pump

signal, which needs to be large for a third-order non-linear conversion, overlap

the optical carrier frequencies. Furthermore, four-wave mixing, being more

complex, generates more cross terms, which can interfere with the optical

5   carrier signals. As a result, it is more suitable for converting a single

wavelength and is difficult to apply to bulk conversion, that is, the simultaneous

conversion of multiple wavelengths.

Yet another all-optical switch previously proposed is a single-pump

parametric wavelength cross-connect. However, such a parametric wavelength

10   cross-connect is limited to the conversion of a single wavelength for each non-

linear optical element provided.

SUMMARY OF THE INVENTION

The present invention comprises a method and apparatus for multiple-

15   band, optical switching using, for example, a multi-pump parametric switch

technique. The switching architecture combines band amplification, wavelength

conversion and selective signal conjugation, enabled by the temporal control of

at least one optical pump.

In one embodiment of the present invention, a method of optical

20   switching using a fiber parametric device receiving an optical pump signal from

at least two optical pump sources includes combining a signal from each of the

at least two optical pump sources and an input data signal to produce a

combined signal, where at least one of the optical signals from the at least two

optical pump sources is controllably modulated. The method further includes

25   imparting a second-order non-linear effect on the combined signal such that a

multi-band switched optical signal results. The multi-band switched optical

signal includes at least one replica of the input data signal and at least three

distinct idler bands. As such, the method may further include separating the

combined multi-band switched optical signal into at least four bands comprising

30   the replica of the input data signal and the three distinct idler bands.

In an alternate embodiment of the present invention an optical switch

includes at least two optical pump sources and an optical combiner for

combining a signal from each of the optical pump sources and an input data

signal to produce a combined signal. The optical switch further includes a non-linear optical element for imparting a second-order non-linear effect on the combined signal and at least one optical splitter for separating the combined signal. In the optical switch of the present invention at least one of the optical

5   pump sources is adapted to be controllably modulated such that when the optical signals are combined a logic sequence of the input data signal is controllably switched.

BRIEF DESCRIPTION OF THE DRAWINGS

10   The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 depicts a high-level block diagram of an embodiment of a two-pump fiber parametric switch (FPS) in accordance with the present invention;

15   FIG. 2 graphically depicts an exemplary output of the FPS of FIG. 1 with a signal from both of the optical pumps present;

FIG. 3 graphically depicts an input signal band and the various generated idler bands for multiple combinations of the optical pumps of an FPS in accordance with the present invention;

20   FIG. 4a graphically depicts an output of an embodiment of an FPS in the absence of an input data signal;

FIG. 4b graphically depicts an output of the FPS of FIG. 4a having an applied input data signal and an L-band pump in both the OFF and ON states with two different pump powers for a C-band pump and the L-band pump; and

25   FIG. 5 graphically depicts an output of an embodiment of an FPS of the present invention performing both wavelength conversion and switching.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

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DETAILED DESCRIPTION OF THE INVENTION

Although various embodiments of the present invention are being described herein with respect to a two-pump parametric switch, it should be

noted that the two-pump parametric switch is simply provided as an embodiment of the present invention and should not be treated as limiting the scope of the invention. It will be appreciated by one skilled in the art informed by the teaching of the present invention that the concepts of the present

5   invention may be extended to parametric switches having substantially any number of optical pumps or, more generally, any number of optical sources that may be used to modulate optical signals in the manner described herein with respect to the optical pumps.

        FIG. 1 depicts a high-level block diagram of an embodiment of a two-

10   pump fiber parametric switch (FPS) in accordance with the present invention. The FPS 100 of FIG. 1 comprises two optical pumps 110_1 and 110_2 (collectively optical pumps 110), a non-linear optical element exhibiting a second-order non-linear susceptibility X^2 (illustratively a highly non-linear fiber (HNLF)) 120, five band splitters 130_1-130_5 (collectively band splitters 130), and a pump controller

15   135. Optionally, the FPS 100 may further include a common amplifier (not shown) or multiple booster amplifiers (not shown) to amplify the power of the optical pumps 110 to a desired level. In addition, the FPS 100 may further comprise a variable electrical delay line to be used for synchronizing an input data signal and a pulsed pump (described in detail below). Furthermore,

20   although the FPS 100 of FIG. 1 is depicted as comprising a single pump controller 135 for both optical pumps 110, in other embodiments an FPS in accordance with the present invention may comprise a separate pump controller for each optical pump therein. In addition, the pump controller(s), although being depicted as being located within the FPS 100 of FIG. 1, in

25   alternate embodiments of the present invention the pump controller(s) may comprise separate components outside of an FPS of the present invention.

        In the FPS 100 of FIG. 1, the pump controller 135 controls the output of the optical pumps 110. That is, the optical pumps may be operated at a constant level or may be pulsed (modulated) to perform the switching of an

30   input optical signal in accordance with the present invention (described in detail below). The pump signals from the optical pumps 110 are combined by the band splitter 130_1. The combined pump signals are communicated to the second band splitter 130_2 wherein the combined pump signals are further

combined with an input data signal, such as the illustrated WDM signal. The combined pump signals and data signal are communicated to the HNLF 120. In the HNLF 120, the combined signals experience a second-order non-linearity and a parametric amplification which produces a replica of the input data signal

5 and three distinct idler bands. The input data signal and the three idler bands are subsequently separated by the remaining band splitters 130_3-130_5 as depicted in FIG. 1. As such, one or more of the signals at the output band splitters 130_3-130_5 may be selected as the converted/switched output signal.

The principle of parametric devices driven by two pump waves utilized in

10 an FPS in accordance with the present invention is described in "Parametric amplifiers driven by two pump waves", C. J. McKinstrie, S. Radic and A. R. Chraplyvy, IEEE J. Sel. Top., Quantum Electron. 8, 538–547 (2002), which is herein incorporated by reference in its entirety. Briefly stated, in an FPS of the present invention, the frequencies of the optical pumps are configured such that

15 an input signal frequency is higher than the lower pump frequency (hereinafter "the L-band pump") and the primary idler frequency is lower than the higher pump frequency (hereinafter "the C-band pump). The optical pump frequencies are also chosen such that the L-band pump frequency and the C-band pump frequency are substantially symmetrical about the zero-dispersion wavelength

20 of the non-linear optical element (e.g., the HNLF). In this configuration, the ranges of secondary idler frequencies do not overlap the input signal and primary idler ranges and as such, there is substantially no crosstalk in wavelength-division-multiplexed (WDM) transmission. The inventors determined that the effects of fourth-order dispersion are weaker in this

25 configuration because the signal frequencies are closer to the average pump frequency. Compared to conventional one-pump fiber parametric devices, the two-pump configuration of the FPS 100 of the present invention offers polarization invariance, broadband operation, the ability to generate unimpaired idler signals regardless of the signal spectral position, and an increased

30 Brillouin threshold.

An FPS in accordance with the present invention, such as the FPS 100 of FIG. 1, provides wavelength (frequency) conversion of an input data signal as well as switching capabilities. More specifically, in the FPS 100 of FIG. 1, an

input data signal is converted from one wavelength (or frequency) to four distinct wavelengths (or frequencies) via the second-order non-linear effect experienced by the combined optical signals in the HNLF 120 and the parametric gain provided by the two-pump parametric amplification generated

5   within the FPS 100. That is, the use of the two optical pumps 110 in the FPS 100 of FIG. 1 produces three distinct idler bands (i.e., the signal is either mirrored or translated to the corresponding idler band) which are all capable of being switched simultaneously. The time required for outer-to-inner band conversion (e.g., 2+ to 2-) is substantially the same as the duration of the outer-

10   to-outer band conversion (e.g., 2+ to 1-) with dispersion contributing only a small wavelength-dependent latency.

FIG. 2 graphically depicts an exemplary converted output of the FPS 100 of FIG. 1. In FIG. 2, an input signal is communicated to the FPS 100. The signal band (1-) is simultaneously amplified and replicated within four spectral

15   windows. The generated idlers are either spectrally mirrored (idler bands 1+ and 2+) or translated (idler band 2-) replicas. Spectrally mirrored idlers are signal conjugates, which offer the potential for mitigating transmission penalties by regenerating the original input signal from the conjugate after transmission. The four-band nature of the two-pump FPS 100 allows for considerable

20   flexibility in selecting the properties of a converted band. Outer band placement of the signal (1-) depicted in FIG. 2, results in an inner band non-conjugate (2-). A signal positioned within any of the two inner bands (1+ and 2-) generates an outer band non-conjugate.

In an FPS of the present invention, such as the FPS 100 of FIG. 1, the

25   inventors determined that the removal of the signal from either of the optical pumps 110 causes the simultaneous collapse of the corresponding idler bands and a loss of signal gain. With this principle in mind, the inventors determined that the temporal control of either one of the optical pumps 110, alone, or the simultaneous control of both of the optical pumps 110, may be used to perform

30   efficient multiple-band switching. More specifically, in the FPS 100 of FIG. 1, the pump controller 135 is used to iteratively turn a single optical pump or combination of the optical pumps 110 ON and OFF (i.e., modulation of the optical pumps) to produce a desired multi-band switched output signal.

FIG. 3 graphically depicts an input signal band and the various generated idler bands for multiple combinations of the optical pumps of an FPS in accordance with the present invention. In FIG. 3, the relative signal and idler band magnitudes are plotted assuming negligible higher-order HNLF dispersion

5 and birefringence. The optical pumps are either co-polarized or cross-polarized with the input signal. On the left side of FIG. 3, the input signal band is positioned in the vicinity of the operating wavelength of the optical pump operating in the normal dispersion regime (the C-band pump). On the right side, the input signal band is positioned in the vicinity of the operating

10 wavelength of the optical pump operating in the anomalous regime (the L-band pump). λ_0 depicts the zero-dispersion wavelength. Referring to FIG. 3, it is evident that in various embodiments of the present invention it would be preferable to configure the L-band pump as the optical pump of the present invention to be modulated to produce a desired switched output in accordance

15 with the present invention, because leaving the C-band pump constant results in less noise than leaving the L-band pump constant and modulating the C-band pump to perform the switching of the present invention.

For example and with reference to FIG. 1, if the first optical pump 110_1 is a C-band pump and the second optical pump110_2 is an L-band pump,

20 maintaining the C-band pump at a constant level while modulating the L-band pump switches a logic sequence of an input data signal to a desired output logic sequence. For example, if an input data signal, modulated using a 10 Gb/s sequence 1100110111010111001, is input to the FPS 100 of FIG. 1 and the L-band pump is pulsed using a 10 Gb/s sequence 1000011110000000001, a

25 switched signal/idler sequence that is substantially the Boolean AND of the input data signal and the pulsed pump signal is produced and results in the sequence 1000010110000000001. As such, the converted four bands of an input data signal are all switched and as such result in a multi-band switched optical signal.

30 The speed of the switching scheme of an FPS in accordance with the present invention, such as the FPS 100 of FIG. 1, depends substantially on the ability to switch the optical pumps 110 ON and OFF (i.e., modulation of the optical pump). This is because the sub-picosecond time constants of the

parametric process in silica are nearly instantaneous when compared to current data rates (< 1Tb/s). Although in the description provided above, the controller 135 is depicted as turning an optical pump 110 ON or OFF (i.e., modulating an optical pump) to produce a desired switched output signal, it will be appreciated

5   by those skilled in the art informed by the teachings of the present invention that the ON state may correspond to a signal that is above a predetermined threshold and the OFF state may correspond to a signal that is below a predetermined threshold (or vice versa) and as such the present invention should not be limited to instances wherein an optical pump(s) is turned

10   completely ON or completely OFF.

In accordance with the present invention, a combination of a broadband FPS of the present invention and slow optical modulators (e.g., ~10Gb/s) may be used to achieve sub-nanosecond switching/conversion over bandwidths exceeding combined C- and L- bands. Furthermore, the use of orthogonally

15   polarized pumps in an FPS of the present invention provides polarization invariant band switching. Conversely, co-polarized pumps may be used when polarization-dependent switching is desired, for example, to discriminate a predetermined signal polarization and the like.

In an experimental setup of an FPS of the present invention, two lasers

20   (optical pumps) were positioned at 1567.0 and 1596.8 nm and phase modulated using 5 Gb/s 2^{31}-1 psuedo-random bit sequence in order to increase the Brillouin threshold to over 400 mW. A zero-chirp Mach-Zehnder amplitude modulator was used to modulate an L-band source (1596.0 nm) with a programmed 10 Gb/s NRZ sequence. The extinction ratio was 12 dB. The

25   optical pumps were amplified using a single optical amplifier. The use of a single amplifier rather than two separate amplifiers simplifies the construction of an FPS of the present invention and simplifies the path length balancing required for narrow idler generation. The amplified signals from the optical pumps propagate through two identical, 0.6 nm wide filters to attenuate optical

30   noise in the signal and idler bands. The measured powers at the input of the HNLF were 180 and 320 mW for the L- and C-band pumps, respectively. The optical pumps and the optical signal were combined at the input of a 1 -km-long HNLF with zero-dispersion wavelength at 1580 nm, dispersion slope of 0.03

ps/nm^2 and nonlinear coefficient, γ, = 10 $km^{-1}W^{-1}$.

FIG. 4a graphically depicts the output of the FPS of the experimental setup described above in the absence of an input signal. Simultaneous pump operation (L-band pump in ON state) results in strong ASE generation across all-four parametric bands, as depicted by the upper curve. In contrast, in the absence of the anomalous pump (i.e., the L-band pump in OFF state), the C-band pump power is more than doubled, as depicted by the lower curve, since a booster amplifier is operated in constant power regime. Furthermore, the OFF state is characterized by the collapse of the four parametric bands, as also depicted by the lower curve in Fig. 4a. The broadband pedestal peaked at 1605nm is observed in the OFF state of FIG. 4a. The pedestal represents ASE from the booster amplifier that is not suppressed by the 0.6 nm cleanup filters.

In the experimental setup, a small data signal, Pin = -20 dBm, was RZ modulated at 10 Gb/s and positioned within the inner parametric band (i.e., λ = 1576.1nm). FIG. 4b graphically depicts the output of the FPS of the experimental setup with the input data signal applied and the L-band pump in the OFF state (lower curve), with the input data signal applied and the C-band pump and L-band pump having respective powers of 280mW and 120mW (middle curve), and with the input data signal applied and the C-band pump and L-band pump having respective powers of 320mW and 180mW (upper curve). The input data signal was simultaneously amplified within the HNLF of the FPS to an output gain of 29 dB and converted (i.e., the created idler bands) to the wavelengths 1557.7, 1587.2 and 1606.2 nm with efficiencies of 24.6, 30.5 and 26 dB, respectively, relative to the signal power input to the HNLF. FIG. 4b illustrates an effective conversion range for the FPS in excess of 50 nm with a tuning speed comparable to the rise time of the modulator, which is 30-ps. The extinction ratio between the ON and OFF states was measured to be 19 dB at 1557.7nm, 29 dB at the signal wavelength and better than 50 dB at 1587.2 and 1606.2 nm. By holding the C-band pump power constant (i.e., separate C- and L-band boosters), the 1557.7 nm idler extinction was increased by 6.3 dB, thus improving the worst extinction ratio to 25.3 dB.

FIGs. 5a-5e graphically depict the switching of the present invention. For

example and with reference to the previous experimental setup, if a received

data signal is modulated using the 10 Gb/s sequence, 1100110111010111001,

and the L-band pump of the FPS is pulsed using 10 Gb/s sequence,

1000011110000000001 an output data signal would have the sequence

1000010110000000001. FIG. 5a graphically depicts the above described input

data signal and specifically the 10Gb/s sequence. FIG. 5b graphically depicts

the switched 1576.1nm input data signal. It is evident from FIG. 5b that a

resulting converted output signal of the FPS comprises a switched sequence

that, as described above, is substantially a Boolean AND of the logic sequence

of the input data signal and the logic sequence of the pulsed optical pump

signal (the L-band pumps signal).

FIGs. 5c-5e graphically depict the created and switched 1557.7nm idler,

the 1587.2nm idler, and the 1606.2nm idler, respectively. Again, it is evident

from FIGs. 5c-5e that resulting created idlers comprise a switched sequence

that is substantially a Boolean AND of the logic sequence of the input data

signal and the logic sequence of the pulsed optical pump signal (the L-band

pumps signal).

As previously stated, the performance of the switching of the present

invention is limited by the speed and extinction ratio of the modulation of the

optical pump(s). For simplicity, it may be assumed that signal amplification and

idler generation is dominated by the non-degenerate phase conjugated process

(i.e., the spectral separation of the input data signal and the optical pumps is

large). As a worst-case extinction estimate, it may be assumed that a) partially

degenerate (one pump) phase conjugation provides gain in the OFF pump

state, and b) the signal and idler experience maximal gain (an ideal phase

matching condition) for both ON and OFF states. The extinction ratio may then

be characterized according to equation one (1), which follows:

$$\frac{P^{ON}_{SIG}}{P^{OFF}_{SIG}} \sim \exp(2\gamma \sqrt{P^{ON}_C P^{ON}_L}\, L_{eff}) / \exp(2\gamma \sqrt{P^{OFF}_C P^{OFF}_L}\, L_{eff}) = e^{2\gamma\, L_{eff}(\sqrt{P^{ON}_C P^{ON}_L} - \sqrt{P^{OFF}_C P^{OFF}_L})}$$

(1)

where $P^{ON,OFF}$ are the pump powers in the ON and OFF positions and L_{eff} is the

C.L

effective HNLF interaction length[2]. When only the L-band pump is switched and a single booster with constant output power of 2P is used for the C-band and L-band pumps, the pump powers are $P_c^{OFF} \cong 2P_c^{ON} \cong 2P$ and $P_L^{OFF} \cong aP_L^{ON} \cong aP$, where a depicts the extinction ratio of the L-band pump. The inter-pump Raman interaction is neglected. Thus the worst-case extinction for the switched signal is now characterized according to equation two (2), which follows:

$$e^{2\gamma L_{eff} Pe - \sqrt{2a} \, j} \sim e^{1.3\gamma L_{eff} P}. \tag{2}$$

For the previously described experimental setup parameters ($\gamma = 10 \text{ km}^{-1}\text{W}^{-1}$, $a = -12$ dB, $L_{eff} \sim 1$ km, and $P_{1,2} = 250$ mW) the worst-case extinction ratio is estimated to be -14 dB. The maximal gain assumption is inherently achromatic and should be used for lower-bound estimate of the extinction ratio. Indeed, the observed signal/idler extinctions are better than -14 dB. It should be noted that the worst extinction should be expected during the pump rise/fall times.

Although various embodiments of the present invention were described and illustrated above with respect to a fiber parametric switch (FPS) comprising two optical pumps, it will be appreciated by those skilled in the art informed by the teachings of the present invention that other embodiments of a fiber parametric switch (FPS) in accordance with the present invention may comprise more than two optical pumps. For example, a fiber parametric switch (FPS) in accordance with the present invention may comprise three optical pumps and as such an input data signal when combined with the three optical pumps in the non-linear medium of the present invention, will produce at least six conversion bands. In this embodiment, either a single pump, or substantially any combination of the optical pumps, may be modulated to perform the optical switching of the present invention.

While the forgoing is directed to various embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof. As such, the appropriate scope of the invention is to be determined according to the claims, which follow.